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SUMMARY REPORT SCINTILLATION, POLARIZATION, AND MULTIPATH EFFECTS ON VHF PROPAGATION BETWEEN SYNCHRONOUS SATELLITES AND AIRCRAFT

E. J. MUELLER

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SUMMARY REPORT

SCINTILLATION, POLARIZATION, AND MULTIPATH EFFECTS ON VHF PROPAGATION BETWEEN SYNCHRONOUS SATELLITES AND AIRCRAFT

E. J. Mueller

December 1970

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1.0 INTRODUCTION

Over the past several years, much effort has been expended in an attempt to size the power requirements for an aeronautical satellite system which would operate in the VHF band. One reason for this effort is the uncertainties surrounding the variability of the signal levels due to the propagation path. In particular the allowances that should be made for absorption, scintillation and multipath fading have not been ascertained with a high degree of confidence or agreement. Additionally, the degree to which these same propagation phenomena might affect ranging and position fixing accuracy has not been established.

This report has been prepared to summarize the current state of knowledge regarding tropospheric and ionospheric scintillation and multipath at the VHF frequencies of interest for an aeronautical system serving the north Atlantic oceanic region. Only the effect of these factors on signal level fluctuations will be considered, and this will be done without involvement in aeronautical operational procedures or specific aeronautical telecommunications systems designs.

2.0 SCINTILLATION

2.1 TROPOSPHERIC SCINTILLATION

When satellites are viewed at very low elevation angles, the ray path traverses the stratifications of the earth's tropospheric refractive index profiles such that fading results due to the synoptic meteorological patterns defocusing the lobe pattern of the antenna and/or multipath propagation in the troposphere. Such fading, having fade depths of 5 to 30 db or more, has been experienced on many line-of-sight microwave paths and is known to be essentially frequency independent.(1)

VHF tests employing the ATS-1 satellite at an elevation angle of 5° experienced higher and more frequent fade depths than might have been expected from purely ionospheric irregularities at a mid-latitude station in Maryland.(12) There appeared to be minimal correlation of scintillation with spread-F and little or no correlation with the local magnetic activity index. It is suggested that this data might have contained a combination of tropospheric and ionospheric scintillation.

Tropospheric scintillation was observed by Badillo(10) using the sun as a signal source at four microwave frequencies: 8800, 4995, 2595 and 1415 MHz. These observations are somewhat indeterminate in evaluating the magnitude and time distribution of terrestrial tropospheric scintillation since various point sources on the solar disk vary in intensity, size and number producing variations in solar emission characteristics. Further, although Badillo reports that frequency dependence varies in an undetermined manner, there is no evidence in these tests to refute the observations on terrestrial microwave systems that tropospheric scintillation is essentially independent of frequency. The multiple source characteristics of solar

emission could explain the variations in frequency dependence observed. One significant conclusion drawn by Badillo is that "Scintillation decreases with elevation angle, becoming negligible at 8° and greater."

Since it is generally agreed that an aeronautical satellite system would not attempt to use angles below 10° elevation, and that the aircraft will generally be above the troposphere, it is not likely that this sort of signal fluctuation will be a problem.

2.2 IONOSPHERIC SCINTILLATION

2.2.1 General

The term scintillation has been applied to the amplitude and phase variations resulting from a redistribution of the signal amplitude caused by scattering of a radio wave passing through irregularities in the electron density distribution in the ionosphere. Absorption plays no part in scintillation. Amplitude variations result from the recombination of waves that emerge from the ionosphere with changed phase.(2) The ionospheric irregularities responsible for scintillation are generally much larger than the wavelength (especially at VHF); the usual range reported for either correlation or peak-to-peak shadow being from a few tenths to several kilometers.(3) The height of the irregularities are generally agreed to be in the F-region(9) (11) (19) of the ionosphere with perhaps an additional E-region involvement at middle and high latitudes.

The phenomenon of scintillation has been analyzed by use of models based on phase changing screen diffraction theory.(2)(5) While this approach is useful in attempting to predict or confirm some of the characteristics and dependencies, it has not provided a basis for practical communications system engineering. What is needed is an empirical approach which statistically describes the scintillation in terms of fade depth, duration, and frequency of occurrence with geographic location and other factors as parameters. Such an approach has only partially been started. There is considerable data on both radio star and satellite scintillation, but nearly all of it has been reduced in terms of "scintillation index" which has a number of different mathematical meanings depending on the person using it. None of the definitions however, can be directly related to cumulative distributions desired by the communications engineer. The information contained in the following paragraphs is based primarily on empirical scintillation indicies.

2.2.2 Latitudinal and Longitudinal Dependence

One of the dominating factors in scintillation is geomagnetic latitude. Aarons et al depict the ionospheric irregularity at night, which roughly corresponds to the maximum scintillation regions of the world, as shown in Figure 1.[6] The density of the hatched areas roughly represents fading depth. The high latitude region is better illustrated in Figure 2 which is an update (to be published) of the high latitude irregularity structure during quiet magnetic conditions presented in reference[6].

In order to obtain a more specific picture of the dependence of scintillation on geographical regions, it will be necessary to resort to observations made at a number of widely separated locations. Allen[3] and Aarons et al[6] have provided a start on this by analyzing scintillation index at stations in the high latitude, mid-latitude and equational regions of the world. This work has indicated the following:

a) High Latitudes

Scintillation is present over the entire polar cap with some evidence of lower rates and amplitudes over the northern polar cap than over the auroral oval.[6]

b) Mid-Latitudes

Significantly less scintillation is present in the mid-latitudes between the lower boundary of the sub-auroral region (about 55 to 60° GML) and the upper boundary of the equatorial zone (about 10°-15° GML).[6] Near these boundaries, however, large fluctuations in index are possible and the boundary edge is jagged, especially during magnetic disturbances.

c) Equatorial Latitudes

The longitudinal extent of the irregularity region considered responsible for scintillation is a function of time of day in

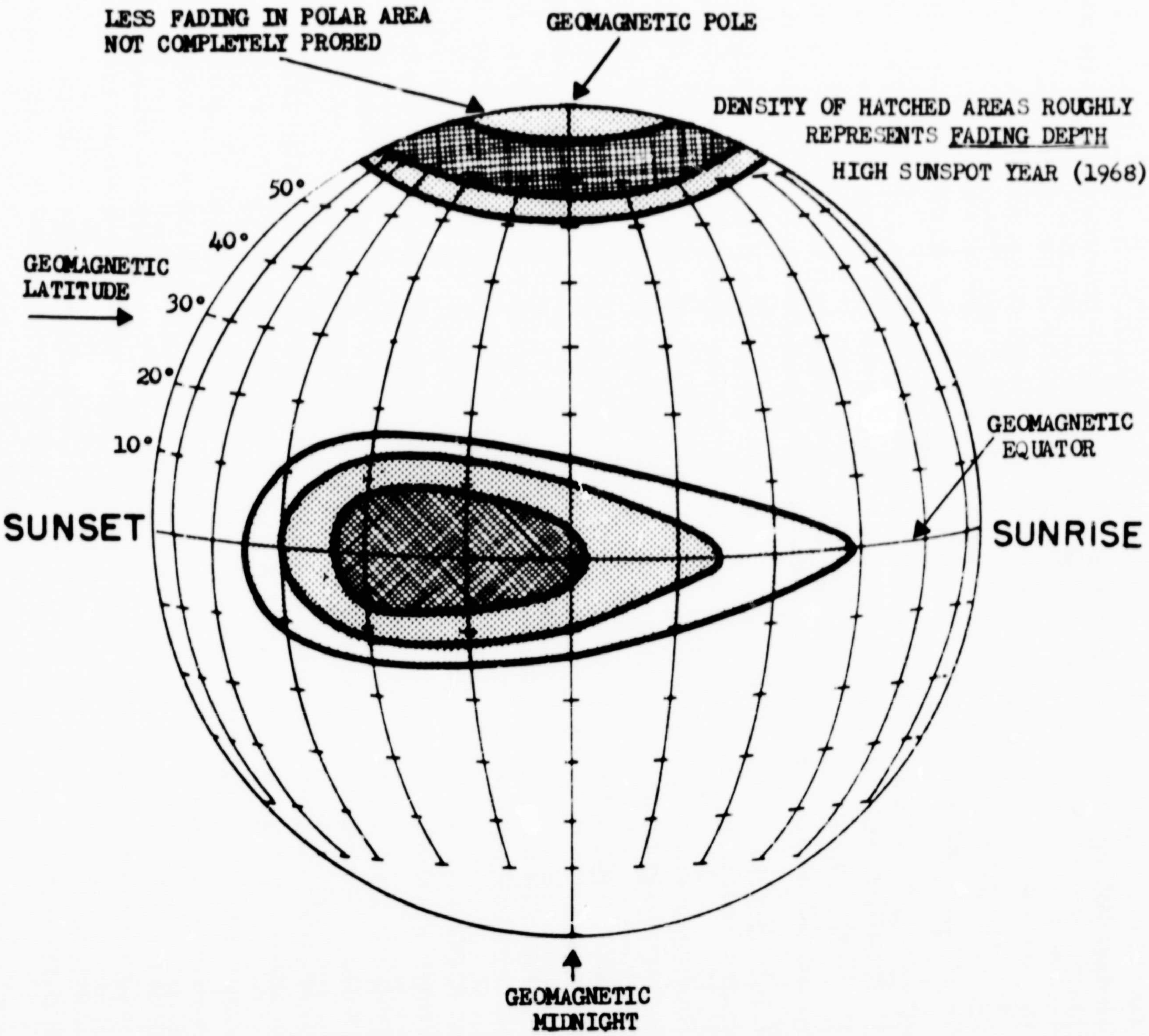

Figure 1. The Ionospheric Irregularity Structure at Night (Reproduced from Aarons, et al, Ref. 6)

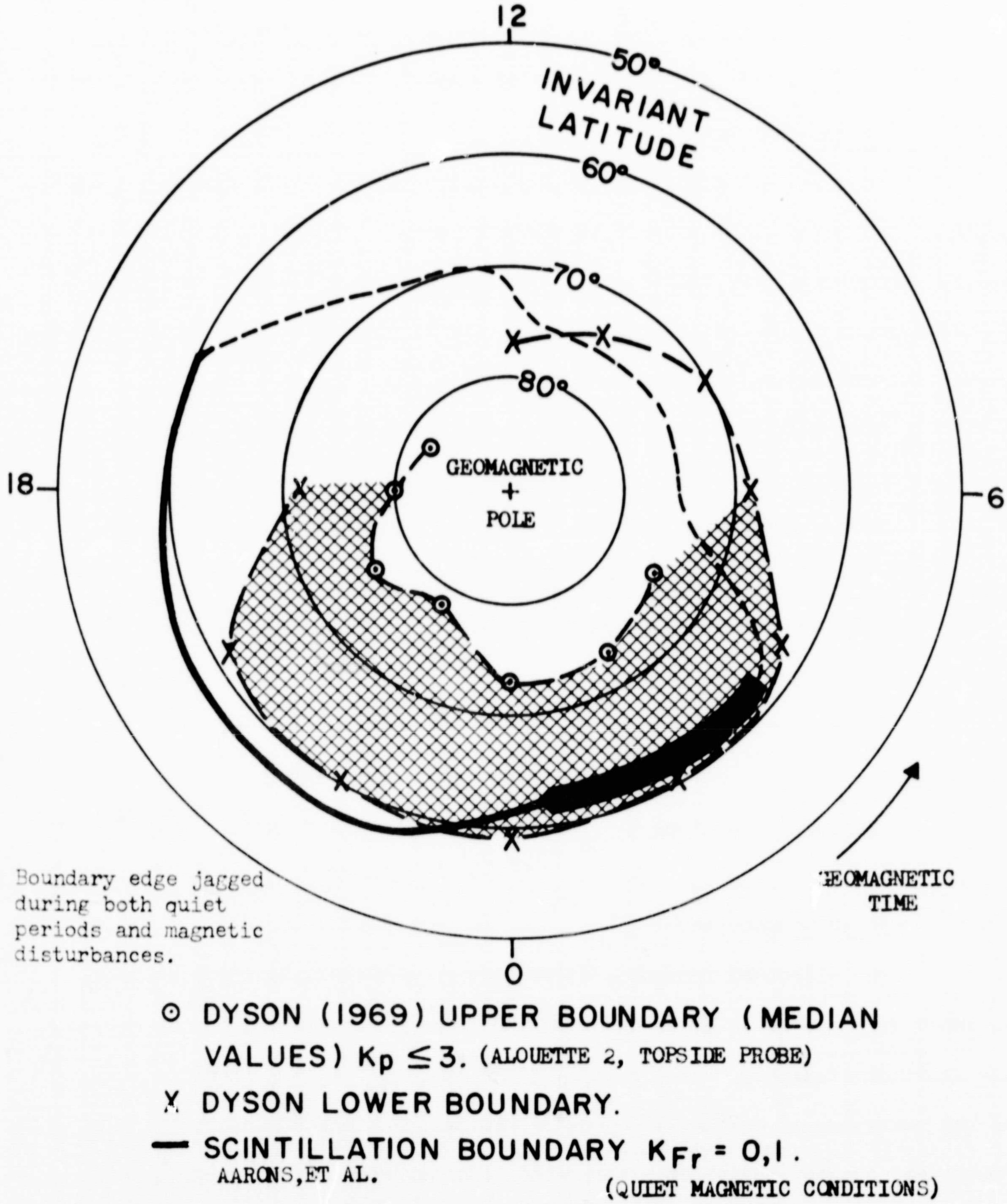

Figure 2. High Latitude Irregularity Structure (Courtesy J. Aarons, Private Communication, to be published in Journal of Geophysical Research)

the equatorial regions with the maximum concentrated around local midnight along the geomagnetic equator (See Fig. 1).

2.2.3 Diurnal Dependence

At high latitudes, high scintillation indices are present over many hours of the day[6] with a definite diurnal period. Minimum scintillation occurs during local daytime with a pre-midnight maximum as shown in Figure 3. It may also be noted that for this data reported from Thule, an anti-correlation exists between fading period and fading amplitude.

At mid-latitudes the diurnal variation favors a post-midnight maximum but there is a lower probability of occurrence than the other regions.[4]

In the equatorial regions, the diurnal pattern is similar to those at high latitudes with a pre-midnight maximum; however, equatorial scintillation tends to start more abruptly reaching maximum fading in a few minutes.[6]

2.2.4 Seasonal Dependence

Information on seasonal dependence is scarce. There seems to be general agreement that a seasonal peak occurs at the equinoxes in the equatorial zone.[4][7] Seasonal dependence at other latitudes is less clear.

2.2.5 Solar Dependence

The effect of increased solar flux on the irregularity picture is to increase the scintillation index on the geomagnetic equator and to decrease the latitudinal extent of the scintillation region.[6] A comprehensive study of the variation of scintillation on 38 MHz observations of Cassiopeia A at Cambridge, England indicated a striking correspondence between mean annual index of scintillation and twelve month running mean sunspot number.[8][3]

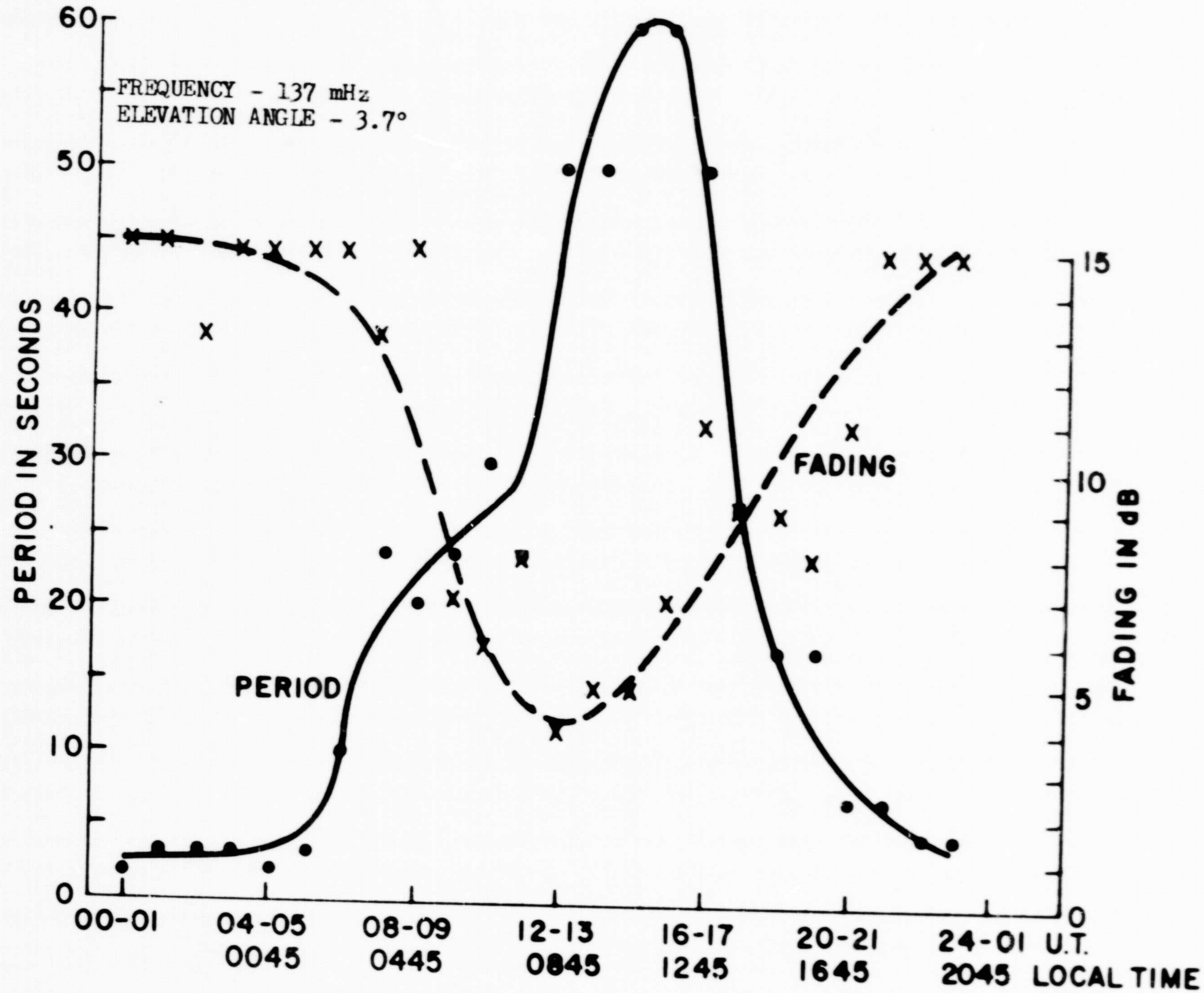

Figure 3. Fading Period and Amplitude for Thule During Quiet Period of Oct. 21, 22, 23, 1968, With A_p's of 2, 1, and 3 (Reproduced from Aarons, et al, Ref.6)

2.2.6 Magnetic Activity Dependence

One of the most pronounced effects on scintillation is associated with disturbances of the earth's magnetic field. At high and mid-latitudes, there is a strong positive dependence on K indices. However, at the equator, there is conflicting information. Studies for the African continent have shown a negative correlation with higher K indices in 1960[9] while data from Peru in 1967-1969 does not corroborate this.[6]

2.2.7 Frequency Dependence

Frequency dependence of scintillation appears to be a function of several parameters. Analytically, using the phase screen diffraction model, the parameters include the thickness of the screen and the viewing distance from the screen. For a thin screen and a viewing distance much less than the Rayleigh distance ($Z_R = \frac{L^2}{\lambda}$ where Z_R is the Rayleigh distance, L is the representative size of the ionospheric irregularity, and λ is the operating wavelength; scintillation is nearly inversely related to the square of the frequency.[3] When the viewing distance is greater than the Rayleigh distance, the depth of scintillation becomes inversely related to the first power of the frequency. Empirically, Allen[3] reports that for low depths of scintillation, the dependence was the inverse square law; but as the depth of scintillation increased, the dependence flattened.

2.2.8 Elevation Angle Dependence

The variation of amplitude scintillation with elevation angle is not well known. Lawrence, et al[2] predicted a dependence of the cube of the secant of the zenith angle employing plane-ionosphere geometry and assuming the irregularities to be spherical in shape. They report the results of several workers which indicated that the increase with zenith angle is appreciably less.

Briggs and Parkin[13] theoretically treat the problem for both radio star and satellite cases. Their equations predict (for the radio star case) a square-root-of-the-secant of the zenith-angle dependence when the observer is in the near zone, i.e. when:

$$\frac{\lambda Z_1}{r_o^2} \gg 1$$

where

λ = wavelength

Z_1 = distance from the observer to the irregularity

r_o = the distance where the correlation falls to 1/e in the direction of the transverse field (take as 1 km for irregularities in the F-region)

However, for the synchronous satellite case, the distance to the source (Z_2) must be considered. For such a case, employing a wavelength of 2 meters (150 MHz) the observer is <u>not</u> in the near zone such that the dependence becomes a more complex function of the zenith angle and the distances between the observer and the irregularity (Z_1) and between the irregularity and the satellite (Z_2).

To date empirical data is both sparse and divergent and one estimate is that the indices increase "more or less" as the secant of the zenith angle.[4] Figure 4 shows a comparison among the various correction factors that have been considered. Currently there is insufficient evidence that any of these may be used with a high degree of confidence.

2.2.9 Magnitude and Statistics

2.2.9.1 High Latitude

Observations of ATS-3 at 137 mHz at Thule, Greenland (76.6°N GML) showed fades of 3 to 15 db over one day during a magnetically quiet period with fade periods from 2 to 60 seconds (see Figure 3). During an intense magnetic storm, higher amplitude scintillations were observed. Fades of 10 db or more are normal daily occurrences.[14] This data has not been processed in terms useful in establishing requirements as a function of percent time availability. Additionally, the elevation angle to the satellite was 3.7° which may have permitted tropospheric scintillation to contaminate the results.

Observations at 136 MHz on non-synchronous satellites at Fairbanks, Alaska showed somewhat less but still significant scintillation.[15] Figure 5 shows that for three years prior to 1968, an average of 25 percent of the

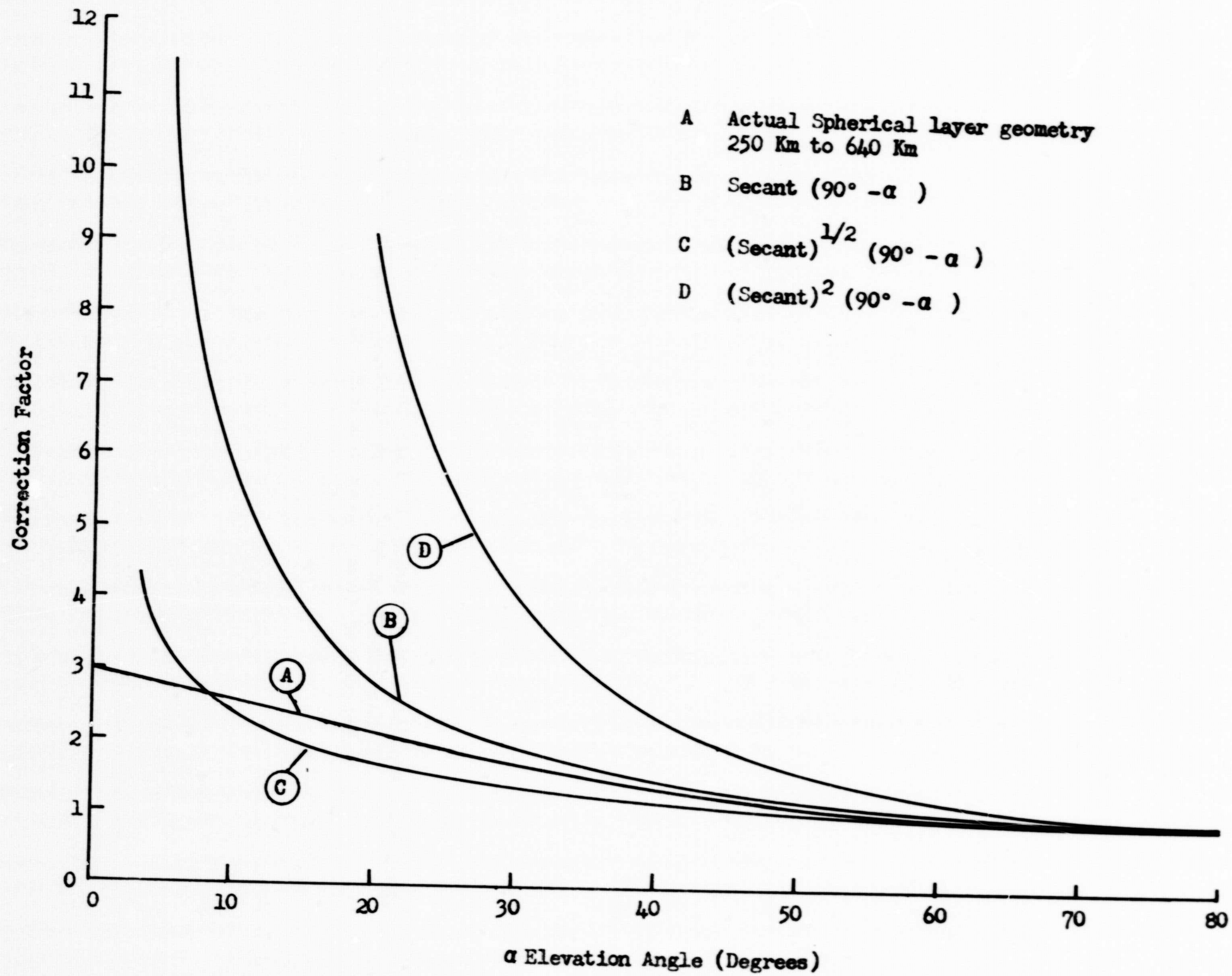

Figure 4. Elevation Angle Correction Factors for Ionospheric Scintillation

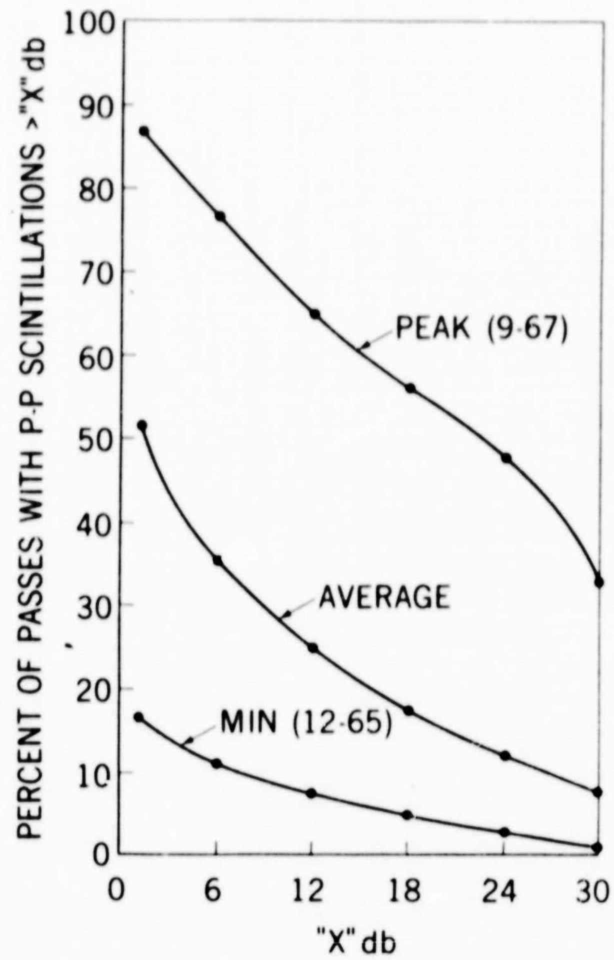

Figure 5 . Amplitude Distribution of Peak-to-Peak Scintillation of 136-MHz Satellite Signals at Fairbanks, Alaska (Reproduced from Coates & Golden, Ref. 15)

data acquisition passes had peak-to-peak scintillations of 12 db or greater. During the most disturbed month (September, 1967), 65 percent of the passes had scintillations greater than 12 db and 35 percent had scintillations greater than 30 db.

ATS-3 VHF signal strength recordings at Narssarssuaq, Greenland consisting of 3581 one hour samples covering September 1968-August 1969 show the higher percentage of occurrence at the higher geomagnetic latitudes.[16] It can be seen from Figure 6 that scintillation indices of 90% or more (equivalent to $P_{max} - P_{min}$ of 12.5 db) occurs about 20% of the time during the worst hours of the day at this location. This should be compared to equivalent data taken at Sagamore Hill, Mass. which may be considered a mid-latitude station (see Figure 7) where the severity seems to be only one fourth as great.

2.2.9.2 Mid-Latitudes

Many satellite and radio star scintillation observations have been reported at mid-latitude stations but unfortunately most of the data has been reduced in terms of scintillation index. For this reason, the results will not be discussed in detail. Information at several widely separated locations may be found in the following references:

Randle Cliff, Md.	Ref. (12)
Sagamore Hill, Mass.	Ref. (17)
Greenbank, W. Va.	Ref. (17)
Boulder, Colo.	Ref. (18)
Urbana, Illinois	Ref. (19)
Baker Lake, Calif.	Ref. (19)
Stanford, Calif.	Ref. (19)

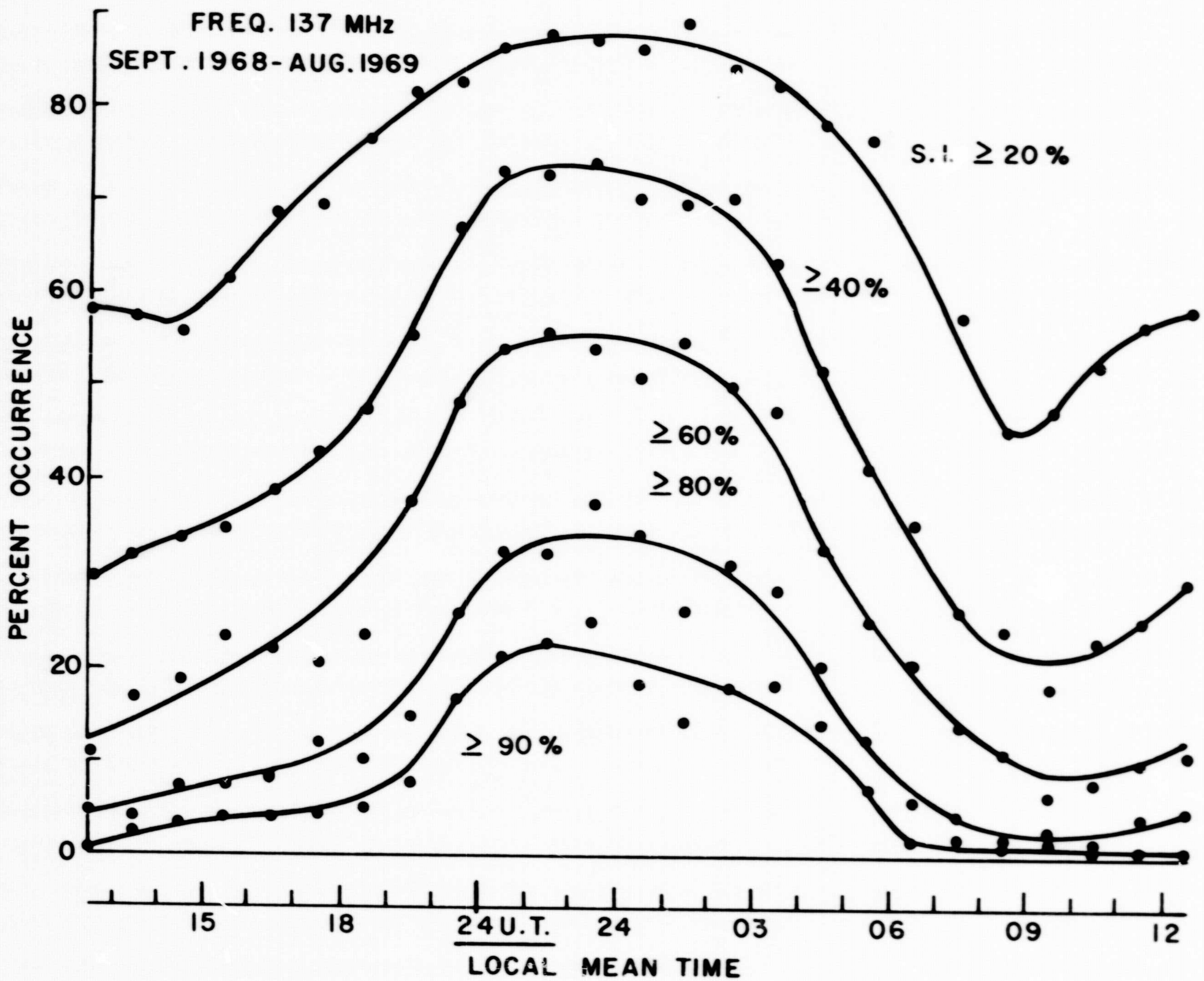

Figure 6 . Percent Occurrence of Scintillation at Narssarssuaq on ATS-3 Signals
(Reproduced from Whitney, Ref. 16)

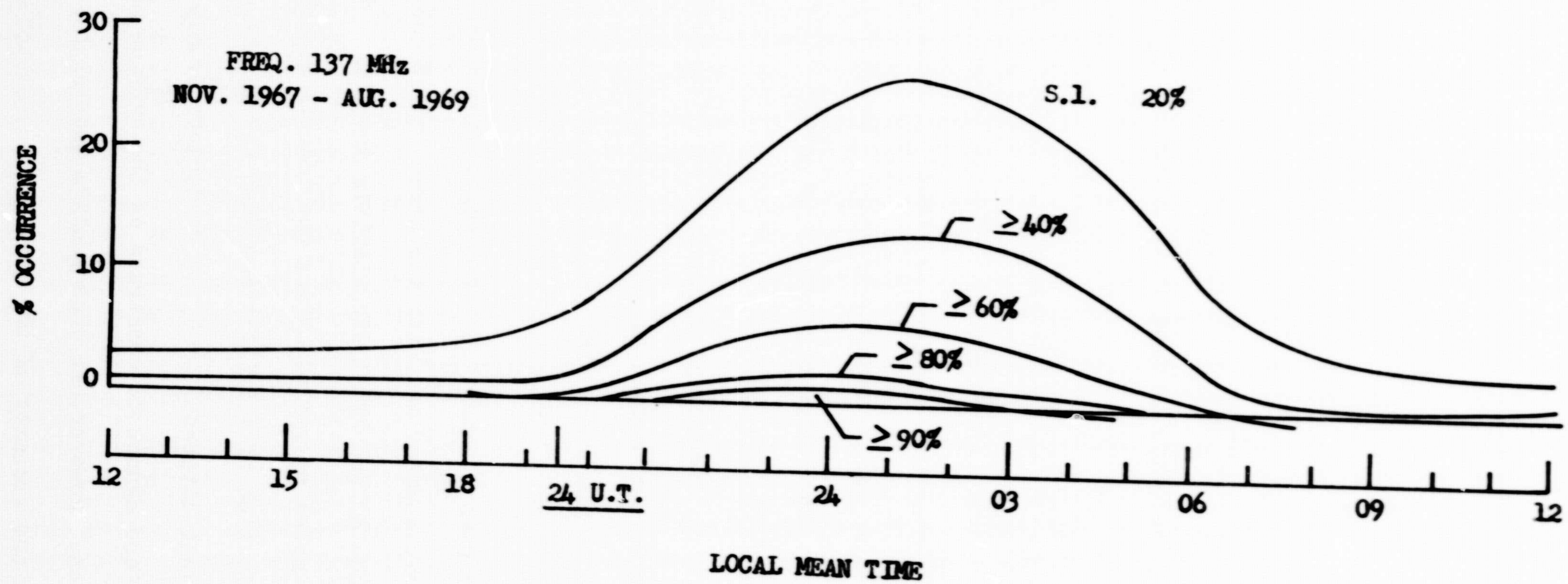

Figure 7. Percent Occurrence of Scintillation at Sagamore Hill on ATS-3 Signals (Reproduced from Whitney, Ref. 16)

2.2.9.3 Equatorial Latitudes

The most extensive statistical scintillation data available in the equatorial region was taken on ATS-3 at 137 mHz and is shown in Figure 8. The more rapid onset of severe equatorial scintillation can readily be seen by comparing these curves with Figure 6 for the high latitude station at Narssarssuaq. Note that 90% scintillation index occurs about 30% of the worst hours of the day as compared to 20% at Narssarssuaq. However, the gross scintillation throughout the day is actually less at Huancayo due to the more rapid build-up and decay.

Further evidence of the severity of equatorial scintillation is shown in Figure 9 where the percent of scheduled minitrack passes missed during a 12-month period at three NASA stations is shown.[20] The highest activity is at Lima which is on the geomagnetic equator. During March 1967 at this station 68 percent of the scheduled passes were missed during the worst hour between midnight and 0100 local time.[15]

One of the significant reports of equatorial scintillation resulted from actual ATS-1 satellite communications support used for backup on the Apollo 11 recovery ship U.S.S. Hornet and the tracking ships Huntsville, Mercury, and Redstone.[21]

During the 12 day period reported, these ships were within about ± 20 degrees of the geographic equator and with the exception of the Redstone, all were within 30° longitude of the ATS-1 subsatellite meridian. Thus, relatively high elevation angles prevailed during the tests. Figure 10 shows a sample of the time distribution of scintillation when the Hornet was at about 11° (about 15° invariant latitude). It depicts evenly weighted data over a 24 hour period and cannot be construed as the average scintillation experienced at that location. However, it does confirm that high scintillation indices may be expected in the vicinity of the geomagnetic equator a significant percent of time.

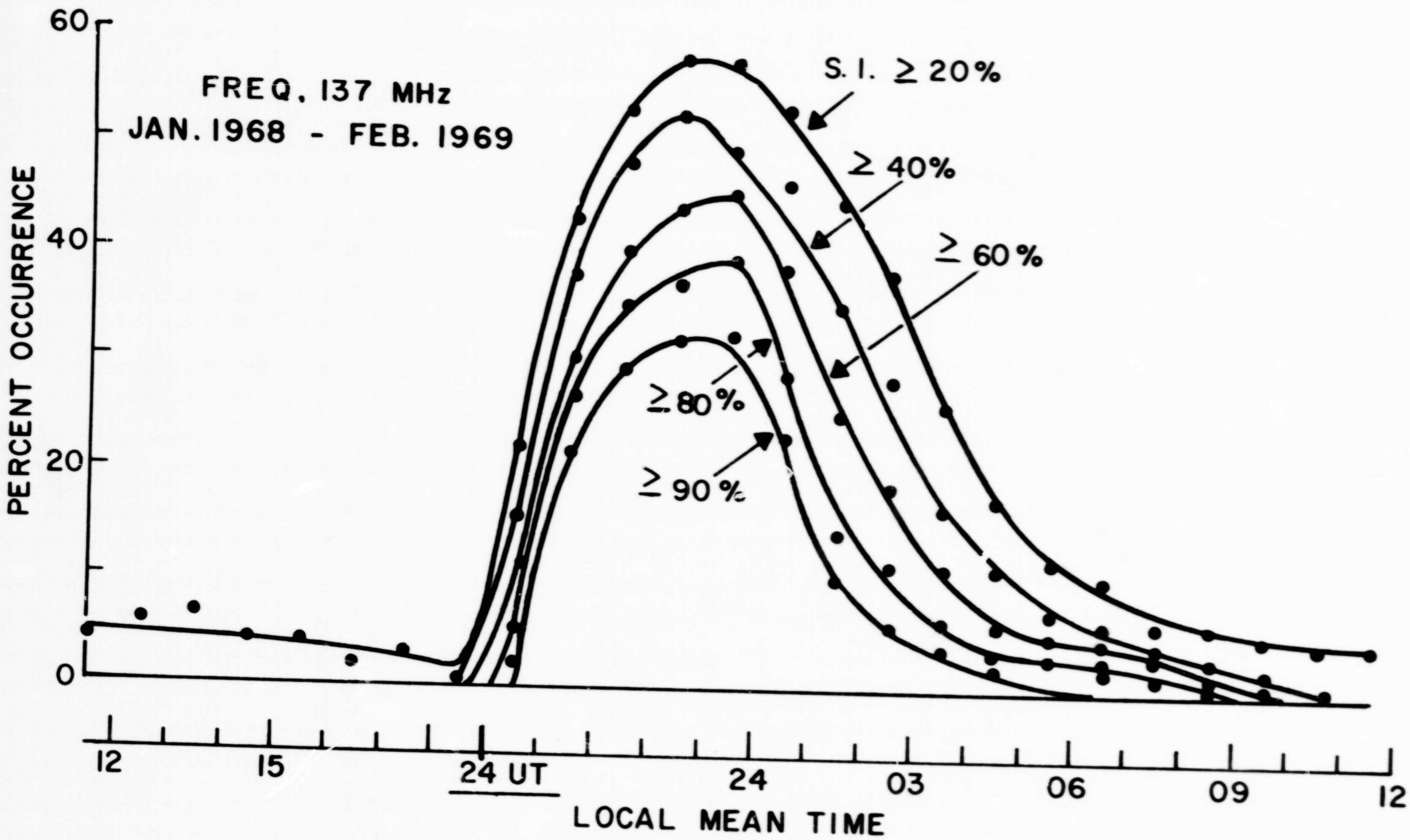

Figure 8. Percent Occurrence of Scintillation at Huancayo on ATS-3 Signals
(Reproduced from Whitney, Ref. 16)

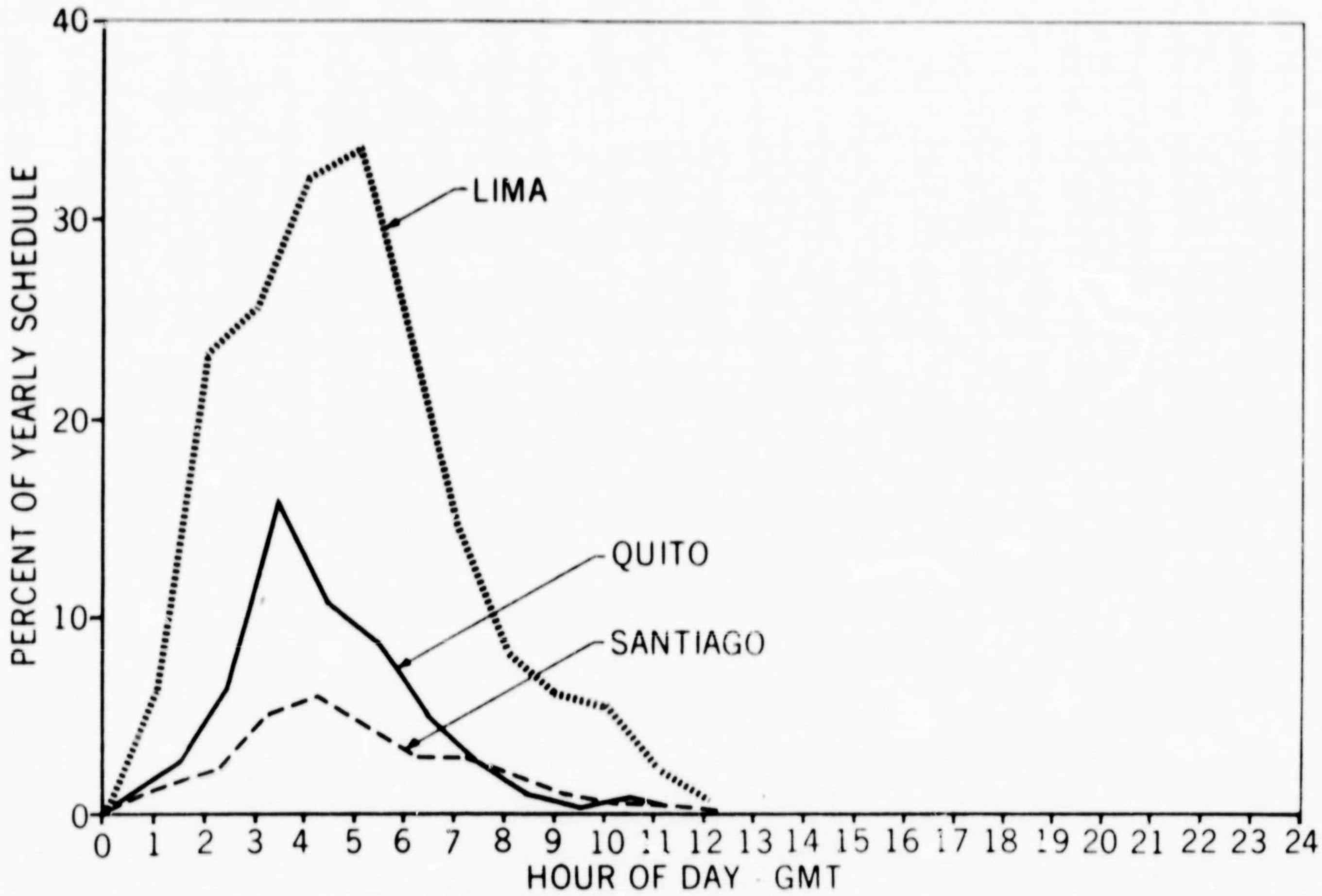

Figure 9. Scheduled Minitrack Passes Missed by Hour of Day During 12-Month Period Due to Propagation Distortion (Reproduced from Coates & Golden, Ref. 15)

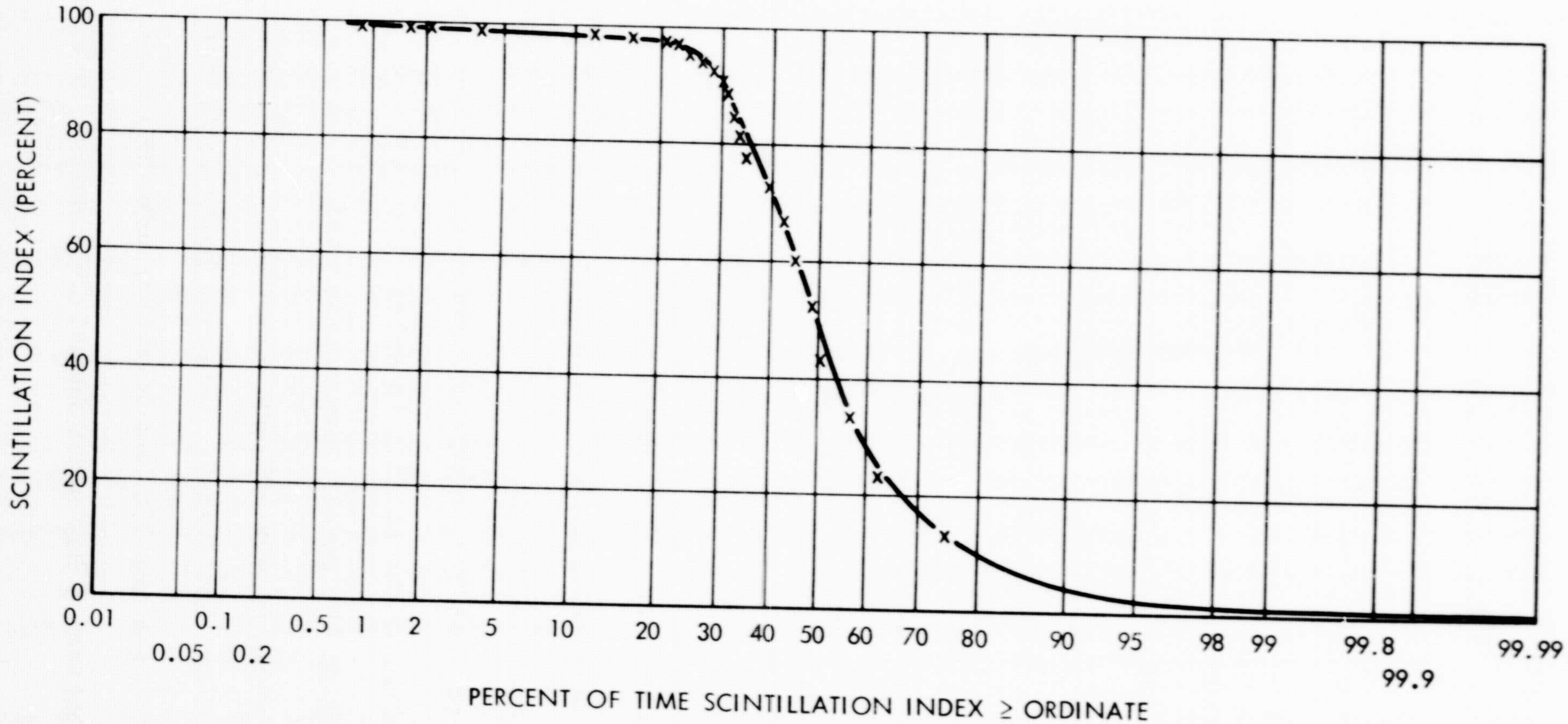

Figure 10. Cumulative Distribution of Scintillation Index, U.S.S. Hornet to ATS-1, July 23, 1969 (Reproduced from Kuegler, Ref. 21)

2.2.9.4 Cumulative Distribution of Scintillation

The magnitude and statistics of scintillation index (SI) presented in the preceding paragraphs are not particularly useful to the systems design engineer since they do not describe the percent of time that a system may be degraded.

Tables 1 thru 4 have been prepared in order to obtain a "birds-eye" view of the useful data on scintillation that have been reduced to date (i.e., those which have been processed in terms of cumulative distribution). It can be seen that only two locations (Hamilton, Mass.* and Churchill, Canada) represent data directly reduced to cumulative distributions. Table 4 shows data converted to cumulative distributions from tabulations of 15 minute scintillation indices[22]. The technique involves the construction of six model distributions representing six quantized levels of scintillation index. Then, the percent occurrence of each of these quantized levels is determined for the various stations, satellites and time periods for which scintillation index data is available. The cumulative distributions are then computed from these models and percent occurrences. This conversion technique has the potential of making available much additional data in terms of cumulative distribution without the need to reprocess the original raw data; however, further effort is required to verify some of the assumptions both explicit and implicit in the technique and to confirm the ability to extend the technique to stations other than those for which the models were constructed.

The largest group of statistical data shown in the tables were extracted from Intelsat I and Intelsat II. The Air Force Cambridge Research Laboratory (AFCRL) monitored the 136 MHz telemetry beacons of Intelsat 1 for 2280 hours of useful data between 5 May and 9 August 1965 and of Intelsat II (F-3)

*Otherwise known as Sagamore Hill, Mass. or U.S.A.F. Cambridge Research Lab.

for 4050 hours of useful data between 11 May 1967 and 17 February 1968. These data, which were reduced by COMSAT* and published by the CCIR (reference 23), are shown reproduced in Figure 11. The data were taken at Sagamore Hill, Mass. (about 53° invariant latitude) with Intelsat I at an elevation angle of 25° and Intelsat II at an elevation angle of 13°.

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*COMSAT has been reverifying their data processing techniques. There is indication that the curves may be changed considerably.

TABLE 1 - INTELSAT DATA (CCIR REPORT IV/1067)

Station	USAF Cambridge Research Lab, Hamilton, Mass.	
Geog. Lat.	42°47'N	
Geog. Long.	70°51'W	
Geom. Lat.	53°N	
Satellite	INTELSAT-I EARLY BIRD	INTELSAT-II CANARY BIRD
Sat. Long.		
Freq.	136 MHz	136 MHz
Elevation	25°	13°
Date of Data	5-5-65 to 8-9-65	5-67 to 2-68
Processed Data Hours	2280	4050
Only SCIN Data Reduced		
All Data Reduced	X	X
Sunspot #	15 (See Note *A)	83 (See Note *A)
Magnetic Act.	8 (See Note *B)	
95%	-0.2 dB	-1.2 dB
99%	-0.8 dB	-4.8 dB
99.9%	-3.0 dB	*C
99.99%	*C	*C
NOTES	1. Azimuth 126.7° 2. Sub-ionospheric coordinates 38°N lat., 64°W long. 3. Column 4 composite of columns 1, 2 & 3 plus non scintillation data 4. Scintillation data less than 2% of all data recorded 5. Data reduced by COMSAT	1. Scintillation data, 17% of total recorded data 2. Data reduced by COMSAT
References	24	34

*A - Sunspot number is average number of sunspots over period of data collection (yearly running sunspot number per CCIR Report 246-1)
*B - A_p number mean average value of monthly readings over period of data collection
*C - Inconclusive data

TABLE 2 - INTELSAT DATA (MONTHLY BREAKDOWN)

Station	USAF Cambridge Research Lab., Hamilton, Mass.								
Geog. Lat.	42°47'N								
Geog. Long.	70°51'W								
Geom. Lat.	53°N								
Satellite	INTELSAT-I EARLY BIRD			INTELSAT-II CANARY BIRD					
Sat. Long.									
Freq.	136 MHz			136 MHz					
Elevation	25°			13°					
Date of Data	5-5-65 to 6-10-65	6-10-65 to 7-17-65	7-19-65 to 8-8-65	5-11-67 to 6-10-67	6-10-67 to 7-10-67	7-10-67 to 8-10-67	8-10-67 to 9-10-67	9-10-67 to 10-10-67	10-10-67 to 11-10-67
Processed Data Hours	21.2	50.7	19.5	156	235	205	20.8	44.3	37.7
Only SCIN Data Reduced	X	X	X	X	X	X	X		
All Data Reduced								X	X
Sunspot# See Note *A	15	15	16	87	67	92	107	77	88
Magnetic Act. See Note *B	6	10	8	25	12	8	9	16	10
95%	-1.8 dB	-1.5 dB	-1.5 dB	-3.2 dB	-1.8 dB	-2.4 dB	-3.6 dB	-1.8 dB	-1.4 dB
99%	-3.2 dB	-3.2 dB	-3.6 dB	-6.6 dB	-3.5 dB	-4.4 dB	-6.0 dB	-3.4 dB	-2.1 dB
99.9%	-5.2 dB	-7.8 dB	-7.5 dB	*C	*C	-6.8 dB	-8.8 dB	-6.0 dB	-3.6 dB
99.99%	-8.6 dB	*C	*C	*C	*C	-9.4 dB	*C	-10 dB	-6.4 dB
NOTES	1. Azimuth 126.7° 2. Sub-ionospheric coordinates 38°N lat. 64°W long. 3. Column 4 composit of columns 1, 2 & 3 plus non-scintillation data 4. Scintillation data less than 2% of all data recorded 5. Data reduced by COMSAT			1. Scintillation data, 17% of total recorded data 2. Data Reduced by COMSAT					
References	24			34					

*A - Sunspot number used from month with most number of data collection days (yearly running sunspot number per CCIR Report 246-1)

*B - A_p number, mean value of daily reading for month with most number of data collection days

*C - Inconclusive data

TABLE 3 - LES 5 & 6 DATA

Station	Churchill	
Geog. Lat.	58.8° N	
Geog. Long.	94.2°W	
Geom. Lat.	68.4° N	
Satellite	LES 6	LES 5
Sat. Long		Drifter
Freq.	254 MHz	228 MHz
Elevation	15° to 22°	0° to 26° 17° Mean
Date of Data	8-28-69 to 10-4-69	8-28-69 to 10-4-69
Processed Data Hours	741	115.2
Only SCIN Data Reduced		
All Data Reduced	X	X
Sunspot # (See note *A)	106	106
Magnetic Act.		
95% (See note 1)	-3.6 dB	-6.8 dB
[illegible] (See note 1)	-9.5 dB	-12 dB
99.9% (See note 1)	-20.4 dB	-22 dB
99.99% (See note 1)	-24 dB	-27 dB
NOTES	1. Data scaled to 136 MHz by 1/f 2. 98% of data recorded showed SCIN activity	
References	35	25

*A - Sunspot number used from month with most number of data collection days (yearly running sunspot number per CCIR Report 246-1)

TABLE 4 - INTELSAT & ATS DATA (REDUCED BY AFCRL)

Station	CAMBRIDGE RESEARCH LAB.		NARSSARSSUAQ GREENLAND	HUANCAYO PERU
Geog. Lat.	42°47'N		60°N	11°S
Geog. Lat.	70°51'W		45°W	77°W
Geom. Lat.	53°N		71.5°N	0°
Satellite	INTELSAT II	ATS-3	ATS-3	ATS-1
Sat. Long		45°W	95°W 45°W	150°W
Freq.	136 MHz	137MHz	137MHz	136 MHz
Elevation	13°	37°	20°	6.4°
Date of Data	5-11-67 to 2-17-68	11-9-67 to 9-29-69	9-17-68 to 8-14-69	7-14-67 to 2-28-69
Processed Data Hours	4212	12330	3314	6518
Only Scin Data Reduced				
All Data Reduced	X	X	X	X
Sunspot # (See Note *A)	83	107	106	104
Magnetic Act.				
95% (See Note *B)	-0.6 dB	-0.4 dB	-2.2 dB	-1.5 dB
99% " " "	-1.6 dB	-1.4 dB	-5.8 dB	-5.8 dB
99.9% " " "	-4.6 dB	-5.0 dB	-12 dB	-12 dB
99.99% " " "	-10.0 dB	-10.0 dB	*C	*C
NOTES	1. 16848 15-minute SCIN values 2. Data reduced by AFCRL	1. 49421 15-minute SCIN values 2. Data reduced by AFCRL	1. During above time ATS-3 moved from 94°W to 45°W 2. 14255 15-minute SCIN values 3. Data reduced by AFCRL	1. 26074 15-minute SCIN values 2. Data reduced by AFCRL
References	22			

*A - Sunspot Number is average number of sunspots over period of data collection (yearly running sunspot number per CCIR Report 246-1)

*B - Converted from statistics on occurrence of scintillation index (conversion technique not yet verified)

*C - Inconclusive data

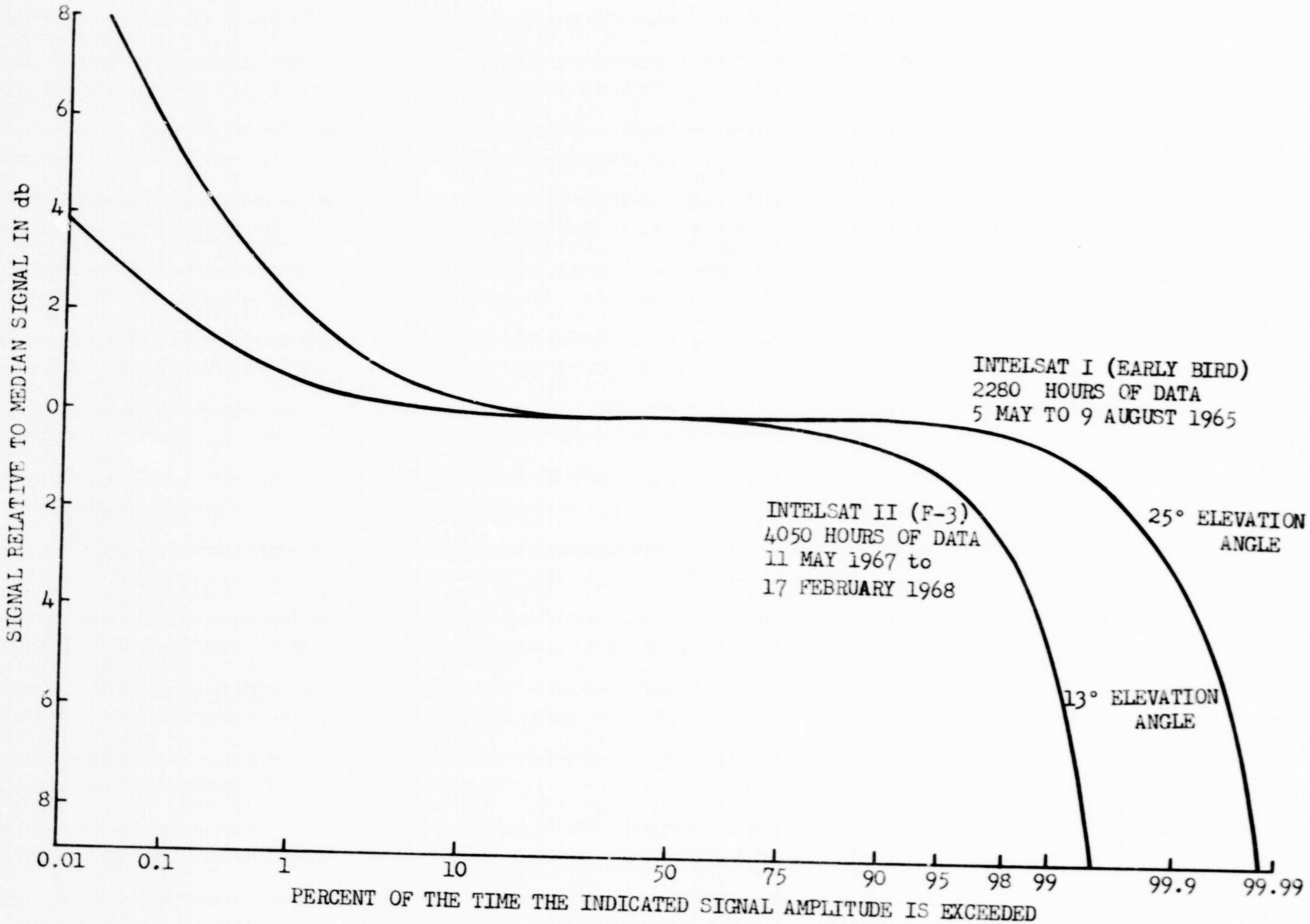

Figure 11. Ionospheric Scintillation of INTELSAT I & II VHF Signals Taken at Hamilton, Mass. by AFCRL (136 MHz) (Reproduced from Ref. 23)

The 1965 data showed that 90% of the fades exceeding 3 db lasted less than 25 seconds while the estimated median duration of 6 db fades was about 5 seconds.[24] In the 1967 data, 55% of the 3 db fades and 63% of the 6 db fades lasted for less than 10 seconds.

A significant difference can be seen in Figure 11 between the 1965 and 1967 data at the "tails" of the distribution curve. The reason for this has not been confirmed but one can speculate on some possibilities. First, assuming the elevation angle dependence to vary as the secant of the zenith angle, the difference between the two curves might be expected to be slightly more than two to one (in db). The observed difference, even at 99%, is far greater than this. Second, the sunspot number was in the order of 15 for the period the data was collected in 1965 and in the order of 83 for the period the data was collected in 1967-1968. According to Aarons,[4] the logarithm of the depth of scintillation depends nearly linearly on the yearly average of the sunspot number. Thus, it is more reasonable to account for the differences in this manner. However, the divergence of the curves implies that even both these dependencies cannot fully explain the difference. Further, it has been noted that on May 25 and 26, 1967, a severe magnetic storm occurred. When the distribution curves for individual months was investigated, it was found that more than half the deep fading responsible for the rapid fall off of the 1967 data occurred in the month of May 1967. This may have also contributed to the differences noted above.*

For convenience in analysis, the data in Figure 11 have been tabulated in terms of four time periods 95, 99, 99.9 and 99.99% of the time in the tables. In addition, the monthly scintillated data that made up these curves have been tabulated. Although some trends with regard to geometric dependence, solar and magnetic activity may be observed, there is no clearly deterministic relationship evident. The Intelsat data taken at Hamilton indicate that

*Data processing methods may also have contributed to the differences.

about 5 db fading for 1% of the time may be experienced at 13° elevation angle in the mid-latitudes about 53° GML during high sunspot periods and about one db may be experienced for less than 1% of the time at 25° elevation angle during low sunspot periods.

The Churchill data taken on LES-5[35] and LES-6[25] shown in Table 3 was scaled from 228 and 254 MHz, respectively to 136 MHz by the inverse frequency law. Thus, the data presented in this table may be somewhat suspect when compared to data taken directly on 136 MHz. However, it does agree with the SI observations that greater fading occurs at the higher geomagnetic latitudes.

Considering that Tables 1 thru 4 represent all the data known to the author to date that has been reduced to cumulative distributions, it is evident that we are severely lacking in ionospheric scintillation data in a form useful for determining systems design parameters, especially in the high geomagnetic and equatorial latitude regions.

2.2.10 Geographic Distribution of Scintillation

A more or less qualitative picture of the geographic distribution of scintillation fading was summarized earlier in this paper. At present this seems to be the most significant geographic distribution available.

Many concepts have been considered for extrapolating the little known data to other geographic locations; however, Allen[3] cautions against attempting to use empirical relationships such as geometric dependence, in regions other than those from which they are derived. More recently, Aarons[13] has suggested that one might consider scintillation to be relatively constant along lines of invariant latitude in the high (and perhaps) mid-latitudes. However, there does not appear to be a sufficient amount of supporting data to apply this theory except on a very "gross" basis.

Since a truly representative geographical picture of scintillation fading is not available, a general idea of its impact on a VHF aeronautical system may be obtained from the experience of actual airlines tests during a major magnetic storm. During the period of October 24-31, 1968, airline tests were conducted employing ground stations at Annapolis, Md., Chicago, Ill., and Wichita, Kansas in communication with three flights between the U.S. and Europe through the ATS-3 satellite.[26]

During this period, which encompassed a major solar flare and associated geomagnetic activity (Max. $K_{FR} = 8$), 24 db peak-to-peak scintillation was experienced at the Annapolis and Chicago ground stations. However, the Wichita station displayed none of the variations reported at the other stations.

The aircraft scintillation data was not analyzed statistically since it would have reflected many other propagation factors, however, it was reported that the link was available 82% of the time and during this time usable voice communication was achieved 59% of the time.[26] The highest latitude reached (on one flight) was about 62° invariant latitude and most of the flight courses were above 55° invariant latitude. Thus, the aircraft was experiencing a mix of mid-latitude and "sub-auroral" scintillation. These aircraft tests show that some consideration must be given to scintillation effects in a practical operating case.

An empirical model has been proposed by Fremouw and Bates[27] consisting of three additive terms corresponding to equatorial, mid-latitude, and high latitude irregularities. Such a model could provide the necessary information for the systems designer provided a sufficient amount of empirical data could be made available to establish the coefficients within the equations and the results presented in terms of fade statistics useful to the engineer.

2.2.11 Discussion

Although there is a large amount of data available on scintillation, meaningful statistics in a form useful to the system engineer is available from only one mid-latitude location (Sagamore Hill, Mass.). Some limited VHF data in useful form is slowly becoming available from other locations, especially Churchill, Canada. Because of quantity limitations and the critical sensitivity of this type fading to the parameters of the ionospheric irregularities, extension of existing data to other conditions (such as different elevation angles, other geographic locations, phases of the sunspot cycle, higher frequencies, etc.) is questionable. On a gross basis, the best estimates at this time would suggest the following scintillation index dependencies:

Elevation angle - (secant of the zenith angle)$^{1/2}$

Frequency - inverse frequency

Sunspot number - logarithmically with yearly average sunspot number

Geographic - constant along given geomagnetic latitude

It is quite difficult at this time to draw any firm conclusions regarding the statistical distribution of ionospheric scintillation or to extend the available data into geographic areas beyond those in which it was taken. Estimates of margin allowance for scintillation at this time can only be made from the limited data contained in Tables 1 thru 4 of paragraph 2.2.9.4 and they would primarily apply to a limited area in the mid-latitudes. Since judgments regarding aeronautical routing, operational procedures and aeronautical tele-communications systems design must be considered in interpreting this data, it is beyond the scope of this paper to suggest a specific system margin requirement.

3.0 POLARIZATION AND FARADAY ROTATION

When a linearly polarized wave penetrates the ionosphere, its vector angle in space is rotated by the interaction between the wave and the geomagnetic field influenced by the integrated electron content along the path.(2) This (Faraday) rotation has a strong diurnal characteristic as a result of the diurnal variation in total electronic content. At VHF frequencies, the difference in rotation between the daytime and nighttime ionosphere may amount to several revolutions and, thus, must be considered in an aeronautical satellite system operation at these frequencies.

As a result of the changes in the geometry of the ray path through the earth's magnetic field and the variation of the field intensity at different latitudes, the rotation will exhibit a latitudinal dependence. Such a dependence was reported in measurements employing ATS-3 on the German research-ship "Meteor"(28) where the number of daily rotations increased as the ship sailed north from 14.5° to 21.5°.

When linearly polarized antennas are employed at both the satellite and the aircraft, severe fading amounting to 30 db or more may result when the polarization of the received signal is orthogonal to the polarization of the receiving antenna. This problem can nearly be eliminated if circularly polarized antennas are employed at both ends of the link; or even if only one antenna is circularly polarized, if one is willing to accept a fixed 3 db signal loss.

The degree to which the effects of Faraday rotation may be reduced depends on the achievable axial ratio (or circularity) of the polarization of the antenna designs. An axial ratio of 2 db in a VHF antenna is reasonably achievable while the VHF aircraft antenna might vary between 2 and 10 db depending on the design and "look angle" to the spacecraft.

The axial ratio of the aircraft antenna is also a parameter in the analysis of multipath fading due to the variation in reflection coefficient as a function of the polarization angle of the incident reflected wave. Levatich[29] has analyzed this problem and presented curves which will be presented and discussed in the "Multipath" section of this paper.

It is generally agreed that VHF polarization loss (neglecting multipath) would generally be between 1 and 2 db* assuming a circularly polarized spacecraft antenna and a reasonably well designed (elliptically polarized) aircraft antenna.

4.0 EARTH REFLECTED MULTIPATH

In satellite-to-aircraft communications links, amplitude fluctuation of the received signal due to addition of out-of-phase signal components reflected from the earth to the direct signal may cause serious rapid fading. The magnitude of the fade depth is dependent on a complex set of variables, the predominant ones being:

a) The aircraft antenna discrimination between direct and reflected signals.

b) The reflection coefficient of the reflecting surface. (This makes sea state an indirect variable.)

c) The elevation angle at which the aircraft views the satellite.

d) The ellipticity ratios of the satellite antenna and the aircraft antenna in the direction of the different propagation paths.

e) The polarization of the incident wave on the reflecting surface. (This makes Faraday rotation by the ionosphere an indirect variable.)

f) The altitude of the aircraft.

*depending upon aircraft attitude

In addition there are several variables which affect the rate of fading, the more significant one being the aircraft velocity. The velocity of waves on the surface of the sea at the reflection point is small enough to be neglected in most cases.

The multipath problem has been examined theoretically by several authors.[29] [30] [31] [32] [33] Levatich[29] presents curves of absolute depth of fading as a function of elevation angle with aircraft antenna axial ratio and three values of aircraft antenna discrimination as parameters. Figure 12 shows these curves where it can be seen that at elevation angles of 10° and an aircraft antenna discrimination of 3 db, about 7 db fade depths may be expected. Since these curves assume a two-ray case and smooth sea conditions, they probably approximate a realistic worst case fade depth.

Experimentally, a series of tests were conducted with the VHF transponders on the ATS-1 and ATS-3 satellites employing a calibrated test spectrum.[33] One of the results of these tests was a three dimensional fading model with amplitude, time and frequency as coordinates. This model demonstrated a selective fading pattern within the 30 KHz test spectrum. It also showed the fade periods to be in the order of 5 seconds for the particular set of flight conditions.

From a practical systems engineering point of view, the probability distribution of fading obtained in these tests may serve as an empirical guide to the fade margin requirements for a VHF system. Figure 13 shows a probability distribution of signal fading where the data was normalized to the same median. This in effect removes the longer term fading associated with the aircraft orientation and aircraft antenna pattern. Thus, the distributions may be considered to indicate primarily the statistics of multipath fading plus small contributions from Faraday rotation and scintillation.

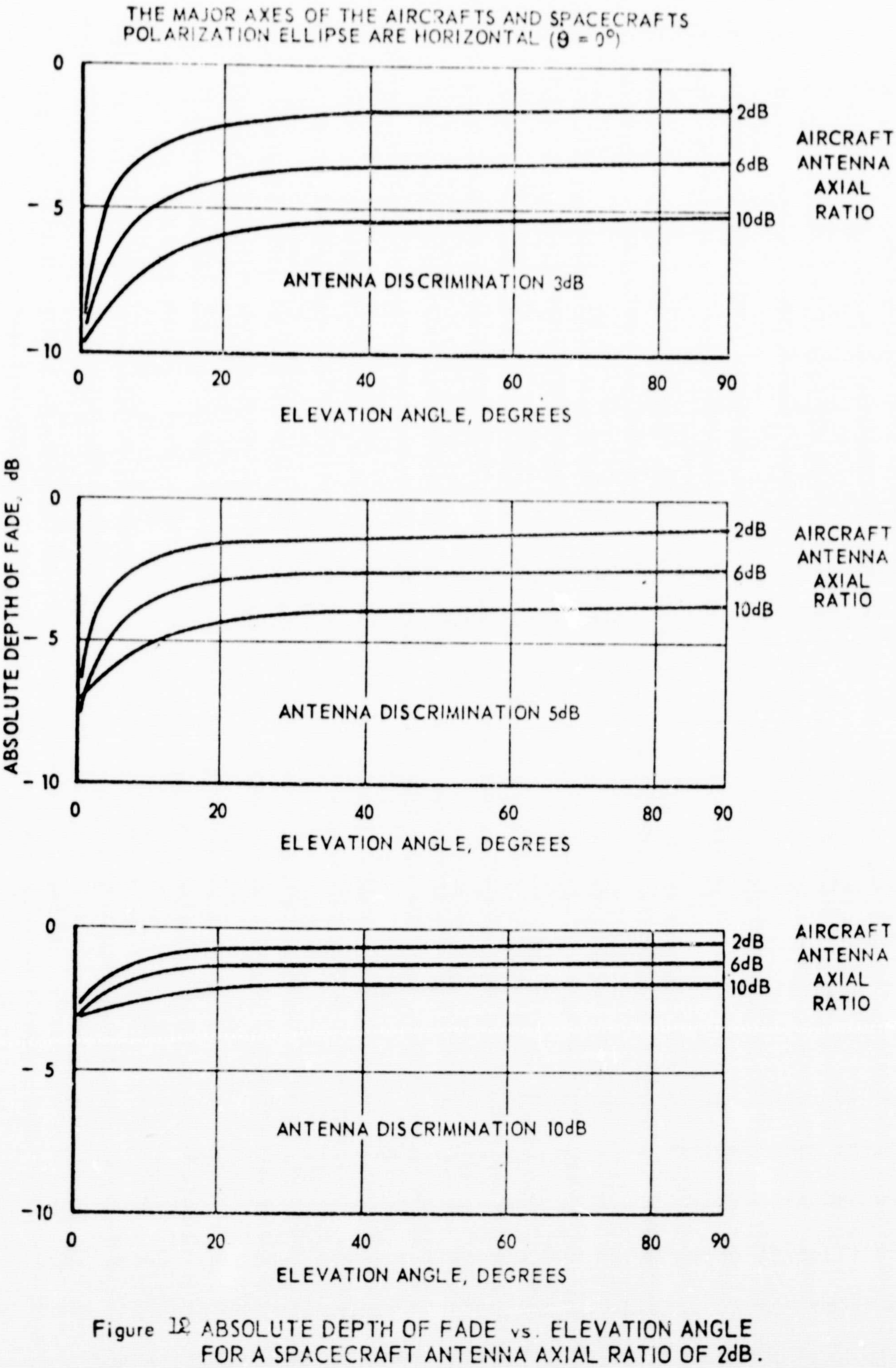

Figure 12 ABSOLUTE DEPTH OF FADE vs. ELEVATION ANGLE FOR A SPACECRAFT ANTENNA AXIAL RATIO OF 2dB.

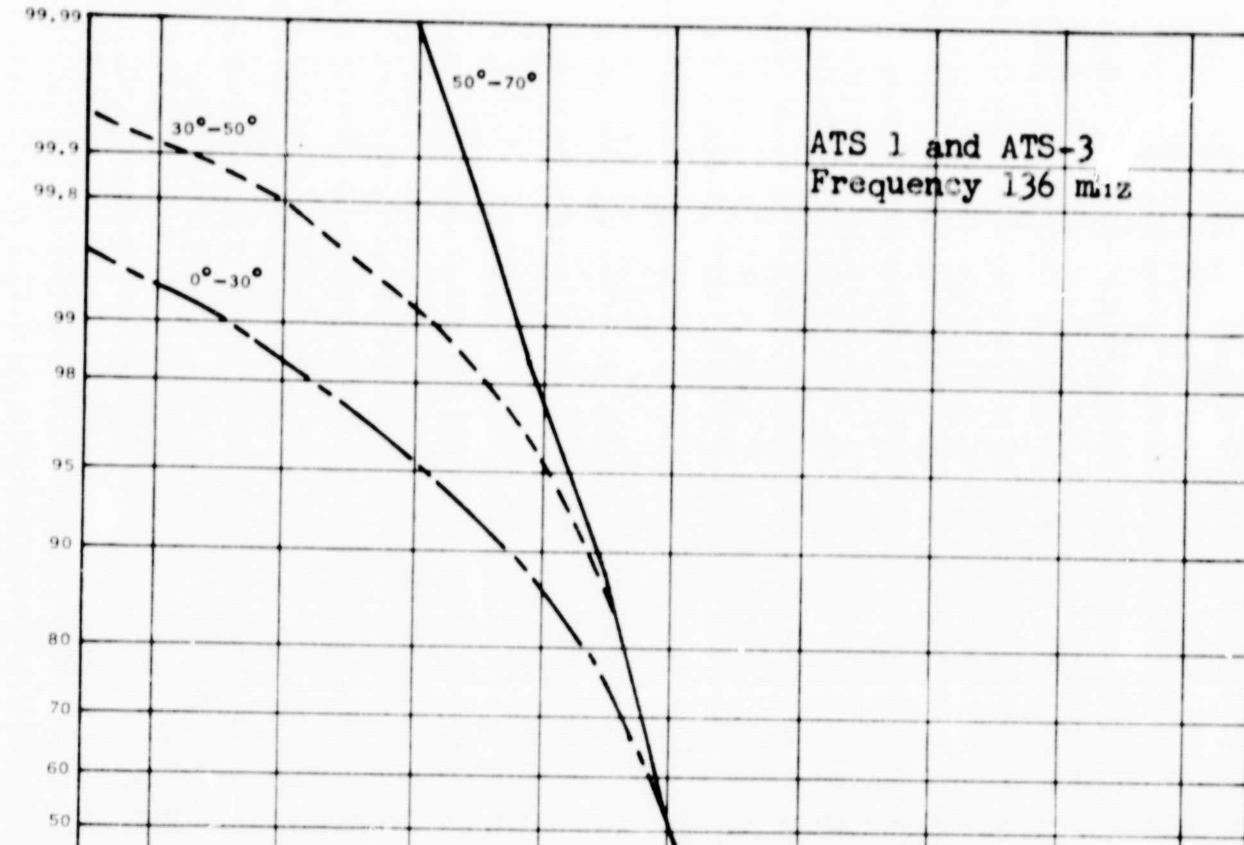

Figure 13. Probability Distribution of Signal Fading
(Reproduced from Bergmann & Kucera, Ref. 33)

5.0 SUMMARY AND CONCLUSIONS

Although considerable data is available on ionospheric scintillation in terms of scintillation index, reliable data taken at 136 MHz in terms of cumulative distributions is available from only one mid-latitude station. This data shows a spread of from 1 to 5 db fading for 1% of the time depending on the elevation angle, sunspot number and other parameters. An attempt to convert data that has been reduced in terms of scintillation index to cumulative distributions requires further verification. Further, the ability to extend the limited cumulative distribution data to geographic areas beyond those in which it was taken is highly questionable especially with respect to frequency scaling and elevation angle scaling. It is suggested that considerable effort remains in both converting prior available data to cumulative distributions and acquiring new data (especially in the high latitude and equatorial regions) before the confidence in a system margin allowance for ionospheric scintillation can be significantly raised.

Since polarization and Faraday rotation fading is so intimately related to multipath fading and antenna characteristics, it seems more reasonable to assess this type of fading along with multipath rather than attempt to ascertain two (db) additive margins. Theoretical studies have indicated that the absolute depth of fade may be in the order of 7 db at an elevation angle of 10° assuming a spacecraft antenna ellipticity ratio of 2 db and an aircraft discriminator of 3 db and axial ratio of 10 db. Actual measurements on the ATS program employing a linear satellite antenna and aircraft antennas representative of early designs indicated that about

4 db or more fading was experienced 1% of the time between 30° and 50° elevation angles and about 7 db or more was experienced 1% of the time between 0° and 30° elevation angles. The data was taken employing early aircraft antenna designs and a linearly polarized spacecraft antenna, therefore any conclusions drawn from them are probably pessimistic when considered in light of what might be achieved on a future satellite program.

It should be pointed out that in establishing systems margins based on the propagation statistics summarized in the report, the fade depths should not be added db-wise but rather the statistics of each type of fading should be combined on a time frame basis of an hour, a flight duration, a day, a month, a year or a sunspot cycle, whichever fits the operational needs of the user.

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